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ACCESS TO A FLOATING WIND TURBINE

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SUMMARY

The offshore wind turbine service industry is now well established with a large number of turbines being successfully operated and maintained. A number of methods and technologies are available to allow the safe transfer of service crews to these primarily fixed monopile installations. The most common of these is the bow transfer method which uses a combination of a high friction fender and a large vessel thrust to minimise relative motion between the bow and the turbine foundation.

An upcoming challenge for the offshore wind turbine service industry will be the increasing use of floating foundations in far offshore and deep water sites. A number of structures are currently being developed and the first commercial floating wind farm is expected to be commissioned in late 2017. The use of floating structures will make it more difficult to ensure crew safety and comfort during transfer operations as the interaction between two floating bodies needs to be considered. Thus, the bow transfer method used to access fixed foundations may not be suitable for accessing floating turbine platforms.

This paper will use a combination of physical and numerical modelling to assess the ability of a wind farm service vessel to maintain contact with a floating offshore wind turbine structure by use of the bow transfer method.

1. INTRODUCTION

Operations and Maintenance (O&M) of an offshore wind farm is substantially more expensive than for an onshore wind farm, it is vital that accessibility limits are known so as to aid planning of the operation.

An assessment of the current state of the art of wind farm service vessels (WFSVs) can be made by reviewing the database of 498 vessels provided by 4C Offshore Ltd, a leading consultancy and market research organisation targeting the offshore energy industry [1]. The vast majority of the vessels listed in that database are high speed catamarans with a cruising speed of 15-25 knots and are generally between 15-24m in length. These vessels can carry a cargo in the range of 3-15t and are typically of aluminium construction, though glass reinforced plastic and other composites are used.

The crew transfer method of vessels is not listed in the 4C Offshore database. Catamarans of the type listed generally use the industry standard bow transfer method described in the summary. A large bollard pull allows the connection between the WFSV and the turbine to be maintained safely for most wave spectra with a significant wave height (Hs) of up to 1.5m [2,3,4,5]. It has been suggested that for the step across transfer the relative motion between the point on the vessel and the turbine docking poles should be essentially zero. [4]. However, a recent industry review showed that crew transfer vessels can safely transfer teams in sea states with Hs of up to 1.8m Hs. [6]

Access to fixed wind turbines can be achieved at higher sea states by use of alternative vessels designs such as the Natilia Bekker small-waterplane-area-twin-hull (SWATH) vessel which can access wind farms at a 2.5m Hs [7]. Another possibility is the use of walk to work systems such as the MaXccess or Ampelmann devices which can be installed on larger service vessels. An Ampelmann installed on a 70m long vessel has allowed safe access to fixed offshore wind turbine in a seastate with a Hs of 3m [8]. The Ampelmann system compensates for the relative motions between the vessel and the turbine, transfer of crew is permitted once relative motions between the stabilised platform and turbine is less than 0.5m in heave [9].

With the advent of floating wind turbines, the problem of access is compounded by the motion of the turbine platform. If using the bow transfer method, excessive displacements caused by loss of frictional contact between the WFSV and the turbine platform may create a serious incident if a transfer operation was being carried out.

Numerical and physical modelling of the interaction of a WFSV with an offshore wind turbine, both fixed and floating, has been used in a number of studies to better understand these interactions. Numerical modelling studies have examined the problem using time and frequency domain modelling and have used a variety of methods to account for the frictional contact between the WFSV and the wind turbine tower.

In one study [10], a numerical method of predicting whether or not a slip will occur was developed by using a qusai-static and dynamic model to describe the system and the Coulomb frictional relationship at the contact point. The major forces of the system were accounted for and a static and dynamic analysis were carried out in the time domain focusing on whether or not a slip would occur. It was found that slips generally occur in the positive Z direction and that the coefficient of friction is of significant importance. This study considered a fixed turbine foundation.

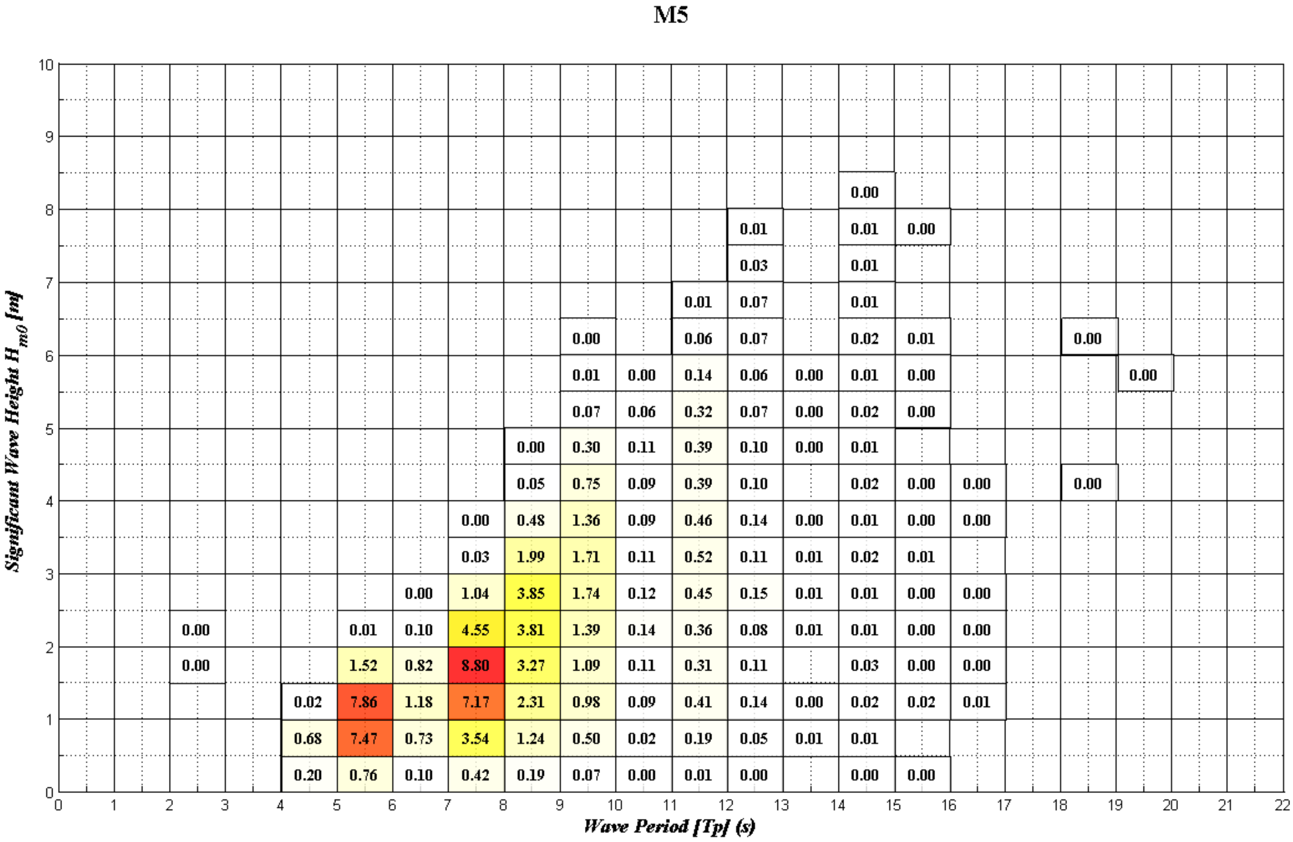

Figure 1: M5 Scatter Plot

In another numerical study [11], a statistical analysis of the docking procedure to a fixed foundation was examined. The bow transfer involved estimating the coefficient of friction and tolerance of the standard deviation of the slips. When combined with the sea state, estimations of accessibility were determined. It was found that upwards slips were more likely to occur than downwards slips. In addition, the peakedness of the spectrum was found to have a negligible effect on the performance assessment.

In terms of physical modelling in this area, a series of experiments were carried out using self-propelled generic catamaran models [3,4,5]. Scale model tests of a 24m WFSV with an active motion compensated gangway were carried out and the vertical forces recorded [3]. It was noted that performance was limited more by stern swamping and propulsion ventilation in stern seas and severe roll in beam seas rather than exceedance of the thresholds of the access system [3]. It was found that for head seas that slips were more common in the positive Z direction. In addition, it was noted that the efflux from the propellers caused an increase in wave steepness, which in turn caused a greater variation in longitudinal force, and consequently slips [5].

Both numerical and experimental investigation of a WFSV at a fixed offshore wind turbine were examined in [12]. In the physical testing, the vessel fender was attached to the WFSV using load cells measuring axial and tangential force. Fender friction was also considered in a separate series of dry tests. In the numerical model, a time domain simulation was created considering the Froude-Krylov forces and forces on the catamaran in addition to the diffraction due to the monopile. The friction contact was modelled as Coulomb friction. Good agreement was found between the numerical and physical simulation [12] and it was shown that the numerical model could accurately determine the risk of a slip occurring. In a follow up paper by the same author [13], the numerical model was further refined with a hyperelastic material used to describe the mechanical behaviour of the fender which was analysed using the finite element method (FEM).

The study discussed previously examined access to a fixed turbine foundation. In terms of access to a floating turbine, a numerical study was presented in [14,15,16]. A two body frequency domain BEM model was used with modelling of the contact point as fixed. The forces at the fixed contact point were recorded during simulations and analysed to determine the required frictional force to maintain contact. The mooring forces of the floating wind turbine were linearised as the entire model was solved using linear systems in the frequency domain. It was found that the wake of the floating wind turbine and the relative motion between the two bodies had significant effects on transfer. Some studies relating to fixed wind turbines are outlined in the following paragraphs.

In this paper, results from both a numerical and physical test campaign will be presented in which WFSV access to a floating wind turbine will be considered.

2. PHYSICAL MODELLING

The configuration used in the physical test campaign is described in this section.

2.1. Test facility

Testing was conducted in the Deep Ocean Basin of the Lir National Ocean Test Facility, Ringaskiddy, Cork, Ireland. The basin, has dimensions of 35 m long x 12 m wide x 4 m deep and is equipped with 16 hinged force feedback paddles capable of a peak wave generation condition of Hs = 0.6m, Tp = 2.7s and Hmax = 1.1m. A movable floor plate allows the water depth to be adjusted to a maximum of 3 m. During testing at a scale of 1:30, the tank water depth was set to 3 m in order to simulate a water depth of 90 m at full scale.

Wave height in the tank was monitored by use of 6 No. 1m conductive wave probes. The probes were calibrated prior to testing and found to have a measurement accuracy of +/- 2 mm.

In order to track the motions of models in the Deep Ocean Basin, a system provided by the Swedish company Qualisys is used. The installation consists of four Opus 3-series cameras, data from which are captured at a rate of 32 Hz and processed using the Qualisys Track Manager (QTM) software.

The Qualisys system requires the installation of reflective markers on all floating models in order to define rigid bodies, the motions of which are tracked in the six degrees of freedom.

2.2. Service vessel

The catamaran was chosen to be representative of a larger type of catamaran vessel such as the Windcats 101, which have a maximum thrust of 19.5t [17]. Thus a catamaran 28.8m long with a draught of 1.2m and a thrust of 20t was studied. The trust was achieved through two lines from the stern of the model as can be seen in Figure 2c. The fender was constructed from rubber. The boat landing was constructed from 10mm (model scale) aluminium pipes protruding 50mm (at model scale) from the face of the stern outer column of the floating wind platform as can be seen in Figure 2a. The overall model setup is shown in Figure 2b.

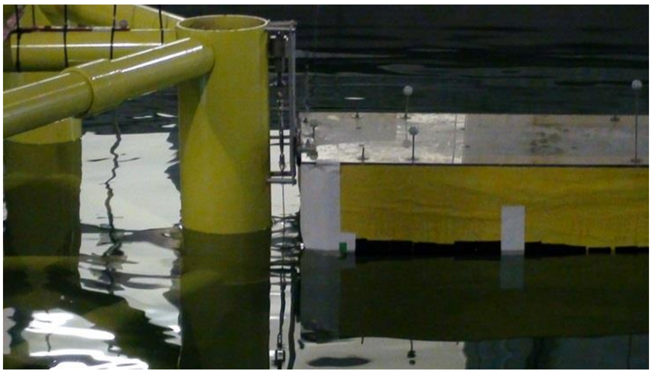

Figure 2a: Physical Model Setup

Figure 2b: Physical Model Setup

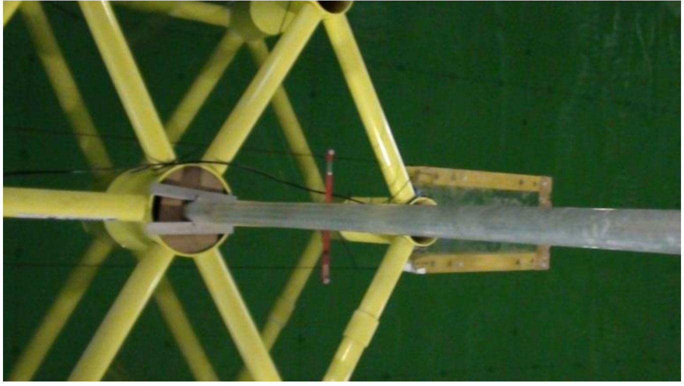

Figure 2c: Physical Model Setup

2.3. Floating Wind Turbine Platform

The floating wind turbine platform considered was the Hexwind Tension Leg Platform (TLP) described in [18]. This platform has been designed to support the NREL 5 MW reference turbine [19]. Platform, tower and rotor nacelle assembly (RNA) mass combined was 221,5440 Kg, Columns are 9m (centre) and 6m (outer), displaced volume was 3911.5 m³. No wind loading was applied during testing and the RNA mass was applied at the full scale RNA centre of gravity (CoG).

2.4. Sea states

The wave conditions considered in the analysis were selected to be representative of the M5 buoy location. A potential deep water site in the Celtic Sea. The measured scatter plot is shown in Figure 1 whilst the location of the buoy is shown in Figure 3.

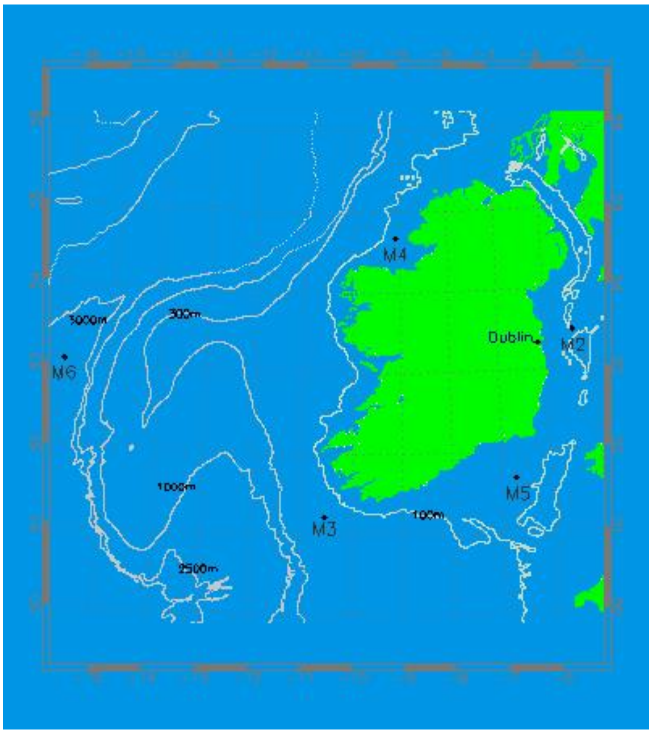

Figure 3: Irish Weather Buoy Network

For each sea-state, 124 random seed wave timeseries (TS) were generated at one-hour full scale duration. The time used in the experiment ~8.5mins model scale (discounting 1 minute start up time) was analysed on a zero up crossing wave by wave basis. The Hmax of each TS was calculated. The Anomaly Index (Ai = Hmax/Hs) of each TS was calculated. The TS with Ai closest to that specified, Ai = 1.6, 1.8, 2, was chosen for experimental testing in the basin. Waves were then Froude scaled to the basin.

Table 1: Irregular Waves at Full Scale

	Hs (m)	Tp (s)	fp (Hz)	Water Depth (m)
1	0.75	5.5	0.182	90
2	0.75	7.5	0.133	90
3	1	5.5	0.182	90
4	1	7.5	0.133	90
5	1.25	5.5	0.182	90
6	1.25	7.5	0.133	90
7	1.5	5.5	0.182	90
8	1.5	7.5	0.133	90
9	1.75	7.5	0.133	90
10	2	7.5	0.133	90

The actual Ai calculated for each sea state is given in Table 2.

Table 2: Anomaly Index (Ai = Hmax/Hs) for Numerical Model

	Ai =		
No.	1.6	1.8	2.0
1	1.599	1.795	2.006
2	1.599	1.791	1.981
3	1.599	1.795	2.006
4	1.599	1.791	1.981
5	1.599	1.795	2.006
6	1.599	1.791	1.981
7	1.599	1.795	2.006
8	1.599	1.791	1.981
9	1.599	1.791	1.981
10	1.599	1.791	1.981

3. NUMERICAL MODELLING

Hydrodynamic parameters were computed using the potential flow theory radiation/diffraction solver ANSYS AQWA for 12 wave directions (30° intervals) and 50 wave frequencies from 3.2s- 30s. The mesh defeaturing tolerance and maximum element size is set as 1.6m and 0.8m respectively for Hexwind and 1.0m and 0.3m for the catamaran.

Time domain analysis was conducted using OrcaFlex v10.1a. Viscous drag forces were applied to the platform using modified drag only Morison's equation elements, using drag coefficients from [20]. The mooring tendons were modelled as Morison's equation elements, discretized into twenty sections each approximately 5m long. Tendon axial stiffness was 10E6 kN.

As the flexible WT tower for tension moored towers influence the pitch natural frequency the flexible tower was numerically modelled using line elements. The catamaran was connected to Hexwind using a hinge connection which only allows relative pitch between the two bodies. Vessel thrust was modelled as a constant force applied at the same location as the experimental model. No wind and current loads were applied.

All simulations were conducted on a single 64-bit desktop PC with 2 x 3.40 GHz Intel i7-4770 processors and 12.0 GB of RAM. The simulation processing time to simulation run time ratio was 1.17.

4. RESULTS & DISCUSSION

In this section, a comparison between the numerical and physical test results is presented in order to assess the performance of the bow transfer method for a floating wind turbine.

4.1. RAO comparison

Firstly, the response amplitude operators (RAOs) determined for the two floating bodies, both numerically and physically, will be examined. An RAO is the ratio of a floating body's motion to the input wave height and is a

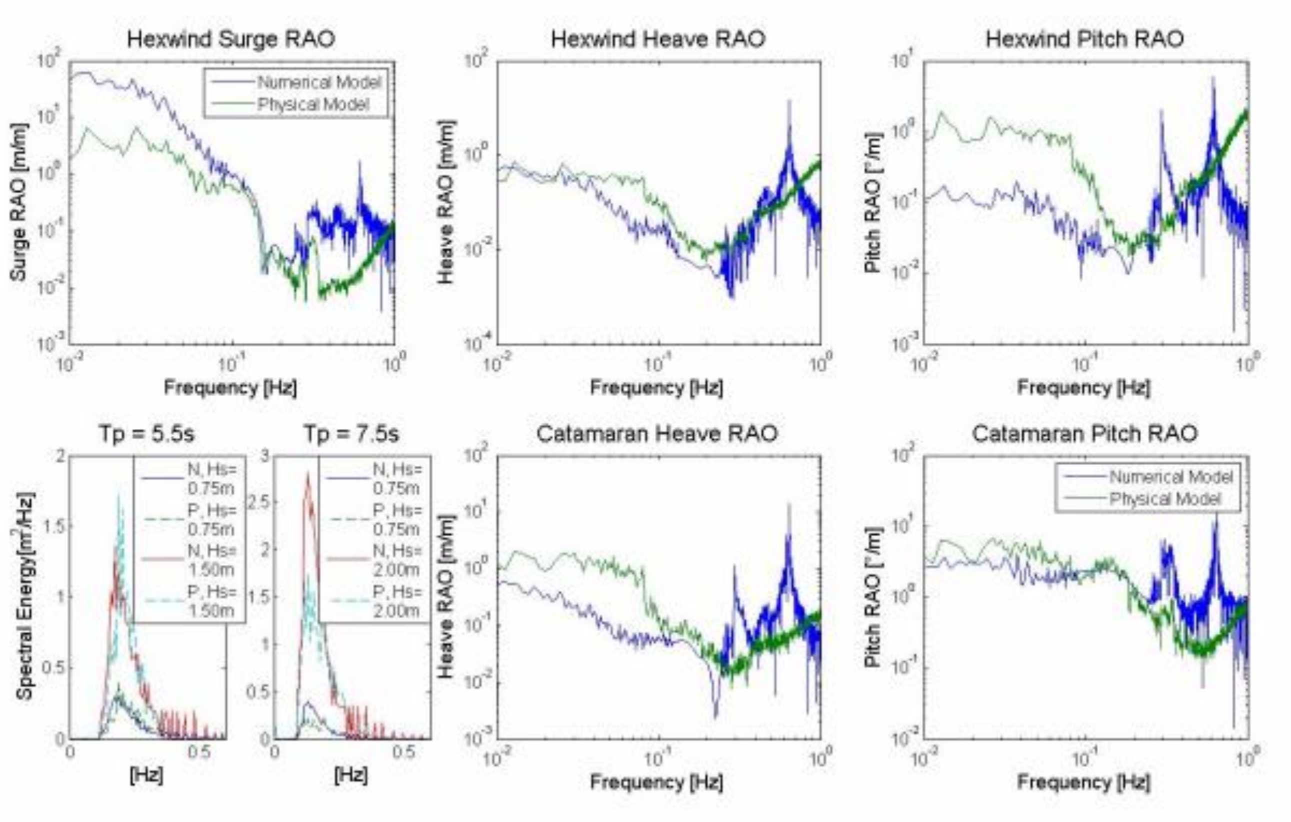

Figure 4: RAO and Wave Spectra Data

critical parameter used to assess the sea keeping behaviour. This study uses the cross-spectral auto-spectral method [21] to calculate the RAO.

$$RAO = H(\omega) = \frac{S_{xy}(\omega)}{S_{xx}(\omega)}$$

where, H(ω) is the frequency response function, Sxy(ω) and Sxx(ω) are the cross-spectral and auto-spectral densities of the input x(t) and the output y(t), in the frequency domain, respectively. A comparison of the RAOs obtain for the two floating bodies by both numerical and physical methods is shown in Figure 3 along with an assessment of the actual wave spectra produced in the wave basin during testing for two selected cases.

As can be seen in Figure 4, the energy content of the waves produced during testing is lower than expected for the Tp = 7.5s and slightly too high for the Tp = 5.5s.

In terms of RAOs, for the Hexwind platform in Surge we see that the numerical and physical model agree well for the wave excitation frequencies especially in the range of 10 – 5s. The numerical model is seen to over predict response close to the natural frequency of the platform which would indicate that the drag coefficients used are too small. This discrepancy could also be explained by the fact that the motions of the physical model are damped by the six tendon load cell cables.

In heave for the Hexwind platform, we see that the numerical model generally under predicts, apart from the exaggerated high frequency peak. Possible reasons for this peak include the fact that the numerical model has undamped hydrodynamic coupling, the discrepancy between the flexible (numerical) and rigid (physical) tower or perhaps oscillation of the mooring tendons.

For pitch in the Hexwind platform, the numerical model generally under predicts, apart from two high frequency peaks. Possible explanations for this peak include the fact that the numerical model does not include sum frequency loads which are dominant in pitch along with the possible reasons outlined for discrepancies in heave.

In terms of the RAO for the catamaran, in heave the rigid hinge coupling in the numerical model results in heave motion being a product of the pitch & heave of the Hexwind model and of the and catamaran pitch. The numerical modelling under predicts response, which indicates that the hydrodynamic interaction could be negatively affecting results, or that reflections dominate results. The two high frequency components in the numerical model appear to be linked to the Hexwind pitch motion.

In pitch the RAO for the catamaran are seen to agrees well Numerical and physical model match well especially well from 12 – 4s. Two high frequency components exist in the numerical model which appear seem to be related to the Hexwind pitch motions. In general terms, the agreement

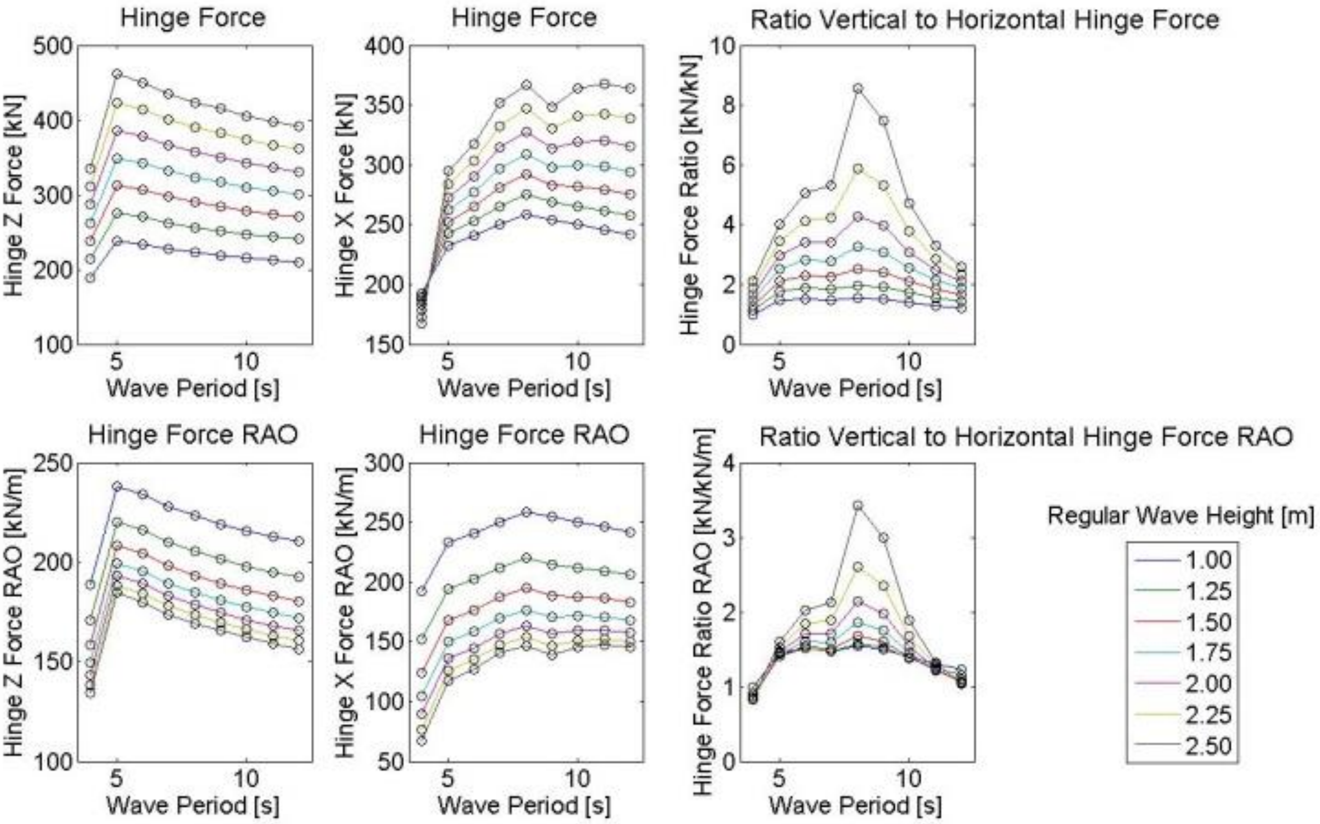

Figure 5: Numerically Modelled Hinge Forces

between the numerical and physical RAO is considered sufficient to allow analysis.

4.2. WFSV / turbine interaction

The forces between the WFSV and the wind turbine platform were not measured during physical testing. In Figure 5, the numerically modelled hinge forces are presented. The hinge force is the contact point between the bow fender and the boat landing as described in Section 3. The peak in the Z force at 5 seconds relates to the catamarans natural pitch period occuring at this period. A significant portion of this force is absorbed by the flexible, compressible rubber fender and smaller slips that do not show up in the analysis. The numerical model is seen to capture the non-linear behaviour of the interacting bodies, as the RAO's of each hinge force demonstrate.

Experiments with irregular wave numbers 8, 9 and 10 with an Ai = 2.0 could not be completed due to the catamaran yawing off the boat landing. This phenomenon was believed to be due to experimental set, the large vessel motion and number of slips occurring. Attempts to constrain the vessel in sway and thus yaw, failed as slippage was also constrained.

In Figure 6, a comparison between the risk of slippage between the bow fender and the floating platform is provided. Results are presented as a probability of exceedance of relative motions in the vertical direction Z. Results are presented for three Ai's for each the 10 sea states summarised in Table 1.

It is indicated in Figure 6 that the numerical model over predicts motions at small wave heights and also then under predict when slips occur. Generally, it is seen that the hinge force seems to be quite significantly over predicted numerically. During the physical tank testing with a bollard pull of 200 kN, and coefficient of friction of approximately 0.8, no slippage was observed for 1.5m regular waves, whilst an increase to 1.75m cause significant slipping. The numerical model predicts that for wave heights of 1.5m force a force of 200 - 300 kN would cause significant slippage.

In Figure 7, the confidence rate of slips not occurring as a percentage of the number of zero crossings is plotted. The confidence rate of slips increases as the vertical movement defining a slip is increased. It can be seen that by defining a slip event as a movement of the fender by 0.1m in the z direction then as the anomaly index increases from 1.6 to 2.0 a confidence rate of 95% suggests the possibility of safe transfers occurring for a 1.5m Hs reducing as the anomaly index increases. Sea states with a 1.75m and 2.0m Hs show a low confidence rate of safe transfers for all cases.

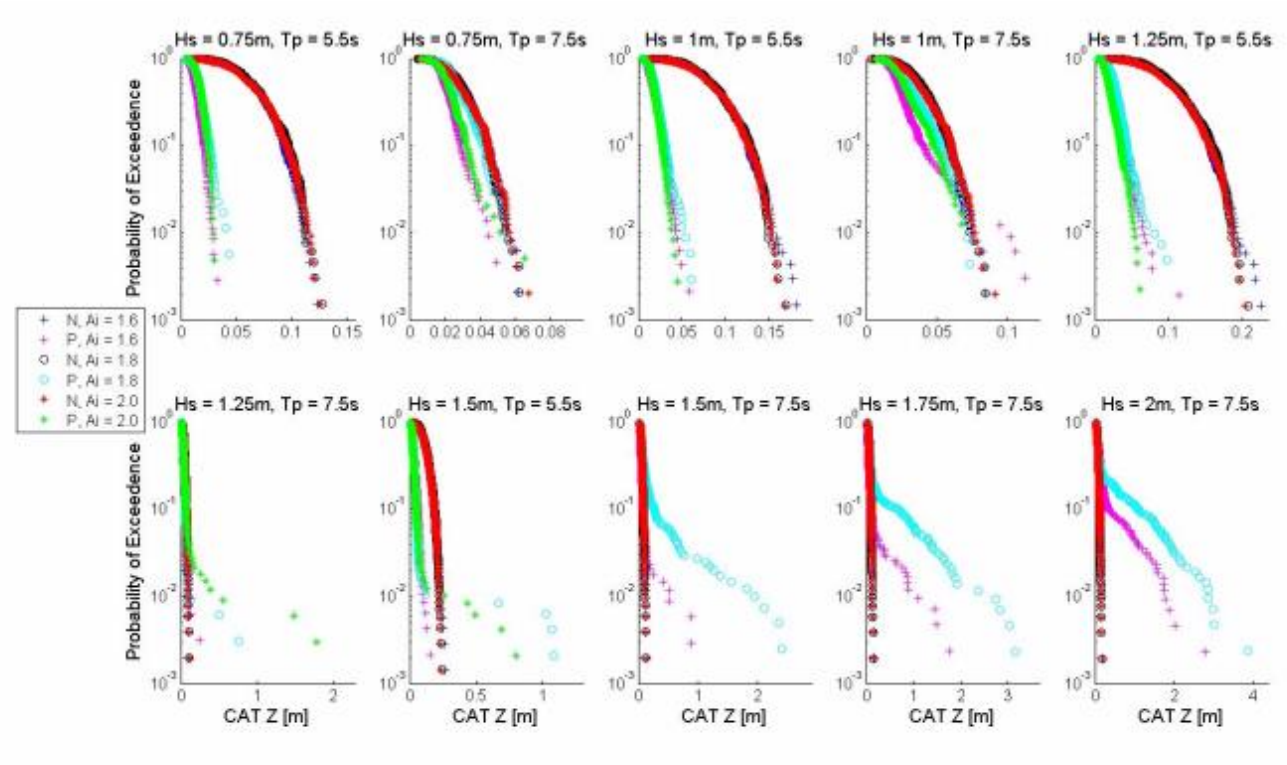

Figure 6: Probability of Exceedance of Relative Vertical Motions

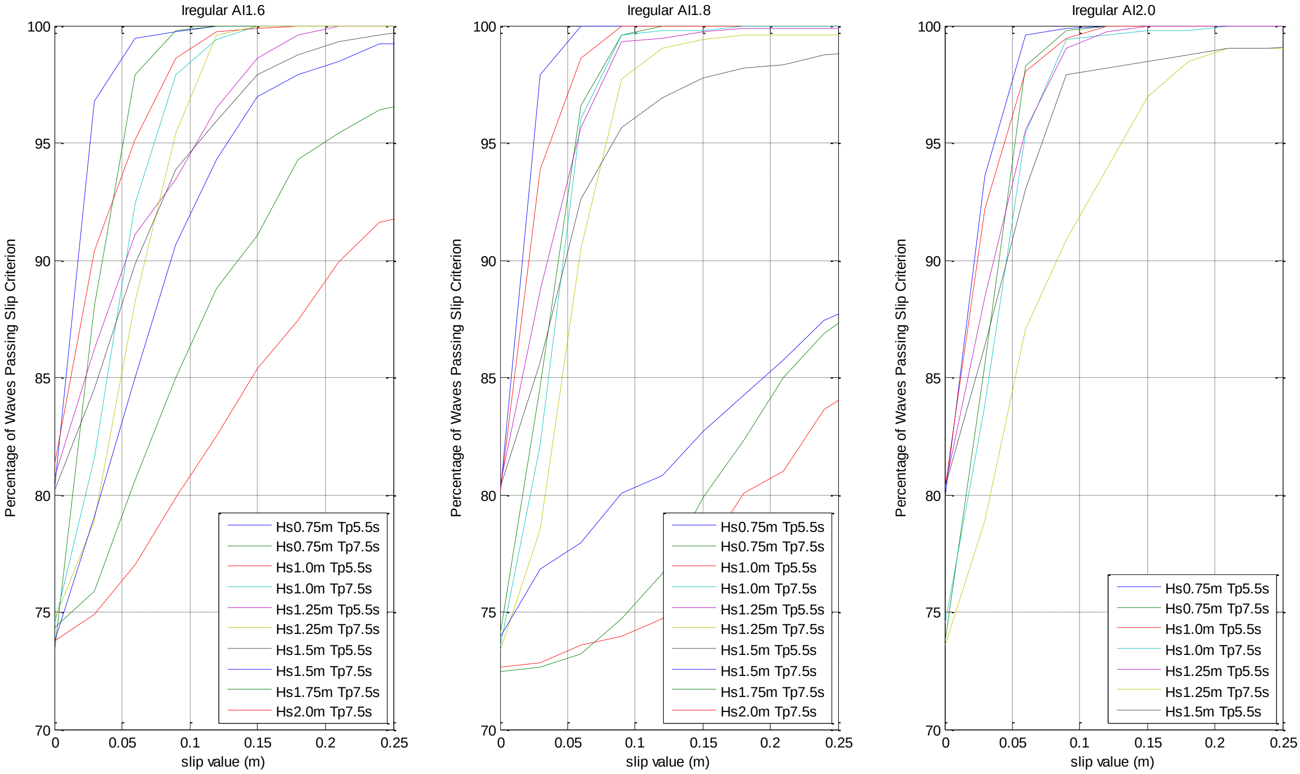

Figure 6: Confidence Rate of Slips Not Occurring as a Percentage of the number of zero crossings

5. CONCLUSIONS

The numerical and physical modelling of a catamaran WFSV docking with a TLP wind turbine were presented in this paper. The response of the interaction between these bodies was studied. The discrepancy between the numerical and physical model showed the requirement for using physical model test to validate the numerical model. The physical model showed the highly non-linear behaviour of the system, which justifies the use of a time-domain model incorporating some non-linearities. The anomaly index has a large effect on the safe transfer limits.

Future work will investigate; the numerical/physical discrepancies, the use of flexible tower during testing, the effect of varying thrust / friction of rubber in testing, measure bow force in testing, and study varying wave incident angles.

6. ACKNOWLEDGEMENTS

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